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Two processes of dense sprays are being studied: (1) turbulence modulation, which involves the turbulent field generated by drop motion, and (2) secondary drop breakup, which can be the rate controlling process in dense sprays. Past work on turbulence modulation highlighted the need for information on drop wake properties for low drop Reynolds numbers (10-1000); therefore, measurements of these flows are in progress using spheres traversing in stagnant glycerol baths. Three wake regions have been identified: a fast-decaying wake (caused by eddy shedding at drop Reynolds numbers greater than 200), a turbulent wake (extending to wake Reynolds numbers of 5-8), and a final laminar wake. Turbulence is not highly developed in the turbulent wakes, yet mean velocities satisfy similarity theory quite well. Current work is concentrating on results at higher Reynolds numbers, to approach results in the literature; studying wakes in turbulent environments; and introducing these results into a stochastic theory of turbulence modulation.

Secondary drop breakup is being studied in a shock tube using water, glycerol and n-heptane drops. A breakup regime map has been developed, defining no-deformation, oscillatory deformation, non-oscillatory deformation, bag breakup, multimode breakup and shear breakup regimes as a function of Weber and Ohnesorge numbers. Results at Ohnesorge numbers greater than 4, show that these conditions are dominated by the no-deformation regime. Current work involves measurements of the dynamics and outcomes of bag and multimode breakup.

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INTRODUCTION

Sprays and spray processes have been studied extensively due to numerous applications. This has resulted in significant progress toward understanding and modeling processes within the dilute portions of sprays. However, existing information concerning the near-injector dense-spray region .. very limited so that phenomena that control initial conditions for the dilute spray region are not understood. Thus, the overall objective of the present investigation is to contribute to a better understanding of aspects of dense sprays.

Present research goals were motivated by findings of an earlier Air Force sponsored investigation (AFOSR 85-0244). The earlier study involved measurements of the structure of large-scale pressure-atomized sprays using holography to observe the properties of the dense-spray region. For the important atomization breakup regime, the flow near the injector exit involves a liquid core, similar to the potential core of single-phase jets, surrounded by a multiphase mixing layer. The multiphase mixing layer is surprisingly dilute, with large relative velocities between the phases and nearly uniform mean gas-phase velocities. Thus, turbulence properties within the multiphase mixing layer are largely governed by drop motion through the gas (effects that have been termed turbulence modulation), rather than conventional mechanisms found in single-phase mixing layers. Similar conditions are encountered over much of the combustion chamber of liquid rocket engines and even in natural phenomena like rainstorms. In spite of these applications, however, turbulence modulation has not received much attention in the past and its study constitutes one phase of the present investigation.

The earlier observations also showed that the multiphase mixing layer consisted of large irregular liquid elements near the liquid surface, which evolved to smaller round drops over the rest of the flow. This supports the classical view of liquid atomization — primary breakup into large drops and ligaments near the liquid surface followed by secondary breakup into smaller round drops. Additionally, it was found that secondary breakup becomes the rate-controlling process within dense sprays at the high pressures of most practical applications, much like the decay of relative velocities and drop vaporization are rate-controlling processes for dilute sprays. Finally, the outcome of primary breakup yielded drops that were near the secondary drop breakup limit. Unfortunately, near-limit secondary breakup phenomena have not received much attention, aside from defining the conditions for the limit itself. The major deficiency is knowledge about the outcome of breakup which is needed to define initial conditions for the dilute-spray region. Thus, study of near-limit secondary breakup constitutes the second phase of the present investigation.

RESEARCH OBJECTIVES

Specific objectives of the turbulence modulation and secondary breakup phases of the study can be summarized as follows:

1. <u>Turbulence Modulation</u>: (i) Complete measurements of the structure of homogeneous particle-laden flows in both air and water, and (ii) develop a stochastic analysis of the flow, accounting for the random arrival of particles (drops), to help interpret the measurements.

2. <u>Near-Limit Secondary Breakup</u>: (i) Complete measurements of secondary breakup to define breakup regimes, rates and outcomes, and (ii) employ phenomenalogical theories to develop effective correlations of the data.

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ACCOMPLISHMENTS

Turbulence Modulation

Introduction . Initial development of theory and measurements for particle/water flows were completed under the previous grant (AFOSR 85-0244). These measurements were extended to particle/air flows and the results were successfully correlated using a stochastic theory during the first year of the present grant. The motivation for carrying out the particle/air measurements was to extend the range of dissipation rates of particle mechanical energy because the theory suggested that this was a dominant flow variable.

The particle/air measurements involved uniform fluxes of round glass beads settling in a stagnant (in the mean) air bath, with continuous-phase turbulence properties being measured using two-point phase-discriminating laser velocimetry. Predictions were based on a simplified stochastic analysis, extending classical analysis of random noise from the theory of signal processing. This involved linear superposition of randomly-arriving particle velocity fields which implies that particle wake properties are a dominant feature of the flow.

The particle/air and water results yielded universal correlations of continuous-phase turbulence properties using variables suggested by the theory. The results show that particle generated turbulence is a unique form of turbulence because mean velocities in the particle wakes contribute to flow properties (since particle arrivals are random). Thus, temporal spectra exhibit a wide range of frequencies even though particle Reynolds numbers are low, the spectra decay according to the -1 power of frequency rather than the -5/3 power found for conventional turbulence, integral scales are large and are related to wake properties rather than particle spacing, and the flow is strongly anisotropic with streamwise velocity fluctuations being roughly twice crosstream velocity fluctuations.

While successful in many respects, the stochastic theory also has deficiencies. One problem is that there is no available information about particle wake properties at the particle Reynolds numbers of interest for sprays (less than 1,000). As a result, it was necessary to extrapolate results from much higher Reynolds numbers (ca. 10,000) and make ad hoc assumptions about conditions when the wakes relaminarize. A second problem is that integrations of particle wake properties needed for stochastic predictions diverge slowly with distance from the particle and must be terminated in an ad hoc manner. Similar difficulties with stochasitc theories have been encountered for problems of sedimentation. This was resolved based on rigorous knowledge of Stokes flow about spheres; unfortunately, lack of reliable information about particle wake properties for appropriate conditions precludes a similar attack on the present problem.

Clearly, the main impediment to further progress on turbulence modulation by particles is lack of information on particle wake properties at particle Reynolds numbers of interest (10-1000). Thus, the main focus of current research on this phase of the investigation is to develop this information. Experimental methods, results thus far, and plans for the next report period are briefly discussed in the following.

Experimental Methods. The particle wake apparatus involves a stagnant liquid bath containing various glycerol mixtures. The test sphere (10 mm dia.) is mounted on a thin wire that is under high tension and is driven through the bath at a constant velocity (200-400 mm/s) by a traversing mechanism. The flow field around the sphere and in the wake is measured by a laser velocimeter which employs frequency shifting to control directional ambiguity of velocities due to the low velocities in the wake. The attachment point of the

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sphere can be traversed so that various radial positions can be observed while sphere motion naturally accommodates streamwise traversing. Data is accumulated as ensemble averages of 30-40 individual traverses.

Results. Thus far, measurements have been completed for sphere Reynolds numbers of 35, 90, 170, 430 and 960. The flow field can be divided into four regimes: the near flow field right around the sphere; the fast decaying wake, where periodic eddy shedding from the sphere enhances wake mixing rates (only seen for sphere Reynolds numbers greater than 200); the turbulent wake region (extending to local wake Reynolds numbers of 5-8); and a final laminar wake region.

The near flow field and fast decaying wake have complex flow patterns. The latter involves decay rates along the axis proportional to distance to the -1.2 to -1.3 power until there is transition to the turbulent wake region. Mean velocities in the turbulent and laminar wake regions scale beautifully with classical similarity theories for these flows with turbulent wakes having virtual origins that are simple functions of sphere Reynolds numbers while the laminar wake has a virtual origin at the center of the sphere. Transitions between these regimes occur when their mean velocity correlations along the axis cross. Turbulence levels in the turbulent wakes are low, befitting the low Reynolds numbers of present wakes; however, this appears to have little effect on the mean velocity properties until transition to a laminar wake occurs.

Plans. Current work is emphasizing measurements of turbulence properties in the turbulent wake and extending the Reynolds number range to approach the classical measurements of Freimuth and Uberoi (at a sphere Reynolds number of 6800). Completing these measurements will provide results needed for very dilute dispersed flows, so that work on the limit problem can begin. Work during the next report period will involve visualization of the flow, emphasizing the properties of eddy shedding; studying wake properties in turbulent environments more representative of particle flows; and modifying the stochastic theory to accommodate the new information on particle wake properties.

Near-Limit Secondary Breakup

Introduction. Measurements of the properties of dense sprays in this laboratory, partially competed under the previous grant (AFOSR 85-0244), showed that the outcome of primary breakup naturally yields drops that are unstable to near-limit secondary breakup. Results in the literature provide some information about breakup regimes at large liquid/gas density ratios and correlations of the time required for breakup. However, information concerning the dynamics and outcomes of breakup is not available: providing this information is the main objective of this phase of the investigation.

The test apparatus needed to study near-limit secondary breakup was developed, and measurements were initiated to define breakup regimes. The main focus of work during the current report period was to complete the study of breakup regimes and to define the dynamics of breakup. Experimental methods, results thus far, and plans for the next report period, are briefly discussed in the following.

Experimental Methods. The test apparatus involves a shock tube with the driven section initially at atmospheric pressure. The drop generator consists of a vibrating capillary tube, with a drop charging system and electrical field arranged so that the spacing between drops is large enough to avoid drop/drop interactions when drop breakup occurs. Drop liquids include water, glycerol mixtures and n-heptane.

Several visualization techniques have been used to observe drop properties when they are subjected to a step change of velocity by the shock wave. This includes stroboscopic backlighting with a copper vapor laser which is recorded with a drum camera, to define breakup regimes; stroboscopic illumination with a flash lamp and still camera, to observe drop dynamics; and single- and double-pulse holography, to observe the outcome of drop breakup.

Results. Measurements during this report period have concentrated on defining breakup regimes and the dynamics of drop breakup. The breakup regime measurements have been limited to large liquid/gas density ratios, but have thoroughly examined variations of drop Weber, We, and Ohnesorge, Oh, numbers by using a wide range of shock Mach numbers and test liquids. Breakup regime maps in terms of We and Oh were initially considered by Hinze and subsequently have been developed further by others. We have added to these maps extensively, defining ranges of We and Oh for the following regimes: no-deformation, non-oscillatory deformation, oscillatory deformation, bag breakup, multimode breakup and shear breakup. At small Oh, transitions to deformation, bag breakup, multimode breakup and shear breakup occur at We=1,12,30 and 80. With increasing Oh, the oscillatory deformation regime disappears and the remaining regimes exhibit increased We for transition. The maximum accessible Oh is 4 (it is very difficult to create drops above this value), however, trends of the results suggest that the no -deformation regime would persist to very high We for Oh>10. This finding is important for high pressure combustion processes because Oh becomes large as drops approach their thermodynamic critical point. Thus, early theories of drop combustion at supercritical conditions, which treated the drop like a spherical puff of gas, may prove to be relevant after all.

Positioning and timing the pulsed holography system is critical in order to observe breakup outcomes; therefore, we have studied breakup dynamics extensively using the stroboscope approach in preparation for holography. The drops deform into disks before breakup occurs, with their drag coefficients progressively increasing from values for spheres to values for thin disks. For all regimes, even during the first oscillation in the oscillatory deformation regime, the diameters of the drops scale quite nicely in terms of well-known breakup time correlations for shear breakup. Maximum diameters of the disk increase with increasing We and decreasing Oh — highlighting the stabilizing effect of liquid viscosity at large Oh. Other characteristics of the breakup processes also have been summarized in terms of We, Oh and breakup time.

Plans. current work is concentrating on holography to identify the outcome of breakup. Thus far, the holocamera has been adapted to the present apparatus and initial tests to define resolution, etc., have been completed satisfactorily. Subsequent work will involve measurements of outcomes within the bag and multimode breakup regimes, i.e., final drop size and velocity distributions. As we gain experience with the holocamera for this application, we also hope to apply holocinematography to study specific conditions in greater detail. These results should help remove current uncertainties about the nature of secondary breakup and provide information that is needed for rational analysis of dense sprays.

PUBLICATIONS

R.N. Parthesarathy and G.M. Faeth (1990) Turbulence modulation in homogeneous dilute particle-laden flows. J. Fluid Mech. 220, 485-514. [Performed under AFOSR 85-0244; paper written and submitted in this reporting period].

R.N. Parthesarathy and G.M. Faeth (1990) Turbulent dispersion of particles in self-generated homogeneous turbulence. J. Fluid Mech. 220, 515-537. [Performed under AFOSR 85-2044; paper written and submitted in this reporting period].

G.A. Ruff, L.P. Bernal and G.M. Faeth (1991) Structure of the near-injector region of non-evaporating pressure-atomized sprays. J. Prop. Power 7, 221-230. [Performed under AFOSR 85-0244].

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L.-P. Hsiang and G.M. Faeth (1992) Secondary drop breakup in the deformation regime. AIAA Paper No. 92-0110.

PERSONNEL

Prof. G.M. Faeth	Principal Investigator	9%
Mr. L.-P. Hsiang	Ph.D. Student	50%
Mr. J.-S. Wu	Ph.D. Student	50% (91/1-)
Ms. H. Younis	Graduate Student	50% (90/8-90/12)

ADVANCED DEGREES AWARDED

None

ORAL PRESENTATIONS

G.M. Faeth, "Turbulence Generation in Homogeneous Dilute Particle/Liquid or Gas Flows," Department o Mechanical Engineering, Wayne State University, Detroit, MI September 1990 (invited).

G.M. Faeth, "Structure and Mixing Properties of Dense Sprays," Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, December 1990 (invited).

G.M. Faeth, "Optical Diagnostics for Combustion Studies," NSF Workshop on Particulate Two-Phase Flow Visualization, Washington, DC, March 1991 (invited).

M. Mizukami, "Particle-Generated Turbulence in Homogeneous Dilute Dispersed Flows," APS/DFD Meeting, Ithaca, NY, November 1990 (contributed).

L.-P. Hsiang, "Near-Limit Drop Breakup from Step Velocity Changes," ICLASS-91, NIST, Gaithersburg, MD, July 1991 (contributed poster paper).

INVENTIONS

None